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(54) **Method and apparatus for monitoring particulates using beam-steered solid-state light source**

(57) An improved method and apparatus for monitoring particulates in stacks or ducts(2) utilizes transmissometer/particulate monitor of the type which has an optical assembly containing a solid state light source (30) of visible light such as a light-emitting diode or a solid-state laser. The light source (30) emits a collimated beam that is split, part of which is focused onto a reference detector (33) that monitors the intensity of the light source, while the other part is directed to a beam-steering apparatus that causes the beam to accurately pass through a gaseous sample to a desired location such as a retro-reflector (20). A position-sensing detector (32) is used in a closed-loop manner to control the beam-steering apparatus. The ratio of the total energy of the de-

tected light beam, relative to the reference detector output, is used to determine the opacity of the gaseous sample for the purpose of providing a basis for correlation to particulate loading of that portion of the particulates that are of a size comparable to the wavelength of light. The correlation to particulate loading is enhanced by a feature of the invention which measures the angular distribution of forward-scattered light to provide information as to the particle size distribution of the particulates. In addition, by steering the beam such that the intensity of scattered light at a preferred scattering angle of 2 to 3 degrees is measured, a measurement may be made that provides a signal that is proportional to the total concentration of particulates independent of the size distribution.

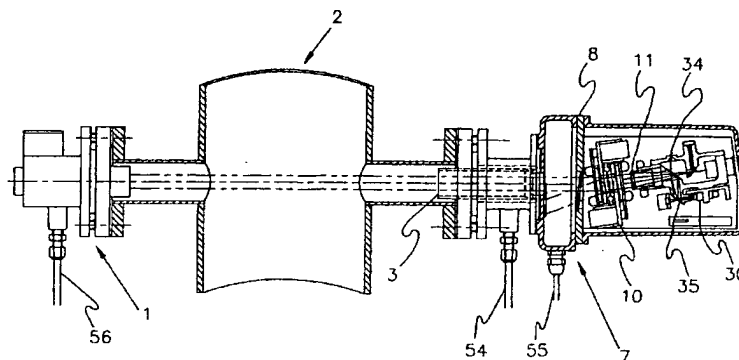


FIGURE 1

## Description

### FIELD OF INVENTION

This invention generally relates to extinction-based particulate monitors of the type wherein the empirically determined particulate concentration is correlated to the optical transmission or opacity of a gaseous sample, measured as a function of the attenuation of a light beam passed through the sample; and to light-scattering nephelometer instruments used to measure particulate concentration and size. Such devices are used for measuring particulate concentration, optical extinction, optical density and/or opacity of stacks or ducts which contain the gases resulting from the burning of fossil fuel or incineration of waste materials, or process gases which contain particulates from industrial processes.

### DESCRIPTION OF THE PRIOR ART

Various government and environmental agencies have set limits as to the amount of particulates and other pollutants that an electric utility or other industry may emit into the air. In some instances, there are additional limitations on visible emissions, also known as opacity. Typically particulate emissions are determined from measurements of the stack gasses as they flow through the stack or connecting ductwork. Opacity monitors, which are also called transmissometers and which will hereinafter be referred to as extinction monitors, along with certain light-scattering instruments, have been used as correlation devices to monitor the mass concentration of dust and other particulates passing through a stack or other conduit. The measurement of optical extinction or optical scattering is compared to the results obtained by drawing an isokinetic sample from the process, with particulate concentration determined via weighing of a filter through which a known quantity of sample was passed, and a correlation coefficient is determined, which establishes the relationship between the optical measurement and the particulate concentration.

Extinction is determined by passing a light beam through the stack gasses and determining the difference between the intensity of the original light beam and the intensity of the light which strikes a detector after having passed across the stack. In single pass monitors the detector is placed on the stack wall opposite the light source. In double pass systems a retro-reflector is located on the stack wall opposite the light source and reflects the light back through the stack to a detector positioned near the light source. In both cases, an appropriate electro-optical method is used to maintain the source at a constant intensity so that changes in source intensity are not mistaken for changes in the particulate concentration.

Most of the double pass transmissometers of the

prior art, such are manufactured by Durag, Irwin Sick, Thermo Environmental, United Sciences, Land Combustion, Rosemont and others, require large mounting pipes, typically 90mm to 150mm, on the stack. The reason for this is related to the need to maintain alignment of the projected beam onto the retro-reflector on the other side of the stack or duct. Such systems are prone to alignment shifts due to thermal expansion and contraction of the stack and the hardware holding the light source, detector and retro-reflector. The mounting ports which hold these monitors on a stack must be large enough to allow for alignment tolerances. However, the mounting ports must be continuously purged with clean air, for the dual purposes of protecting the apparatus and avoiding blockage with particulate deposits. The large amount of purge air required by these large mounting pipes requires the use of large and expensive air blowers which in turn must be fitted with air filters to remove dust from the ambient air. Periodic replacement of these filters, cleaning of optical surfaces that have been fouled by imperfectly filtered purge air, condensation due to humidity in the purge air, and equipment damage from purge blower failure, constitute most of the maintenance associated with transmissometers. The preferable solution to all these problems would be to use dry, filtered instrument air, such as is commonly available at sites where transmissometers are used. However, the large amount, typically 600-1500 liters per minute, of purge air that is required to clean the large mounting ports prohibits this option.

Within the family of single-pass transmissometers are those designs which use either solid-state lasers or helium-neon gas lasers. One of the useful features of these designs is that, because the laser beam is both intense and narrow, the instrument can be affixed to a stack or duct using small mounting ports, which in turn requires the use of less purge air to keep the ports free of particulate material from the gas stream being monitored. This permits the use of instrument air supplies which are commonly available at the job-site, rather than expensive blowers and the attendant maintenance of air filters. An additional advantage is that because laser beams are highly directional, a laser-based system can, in principle, be used over long measurement paths that would be difficult using less intense solid-state sources such as LEDs that diverge. ESCO, MIP and KVB manufacture such an instrument. However, this approach of using a narrow laser beam poses a severe difficulty inasmuch as the beam must be kept aligned onto the detector. For instance, if the laser beam is 0.25" in diameter and must be kept onto the active area of a detector that is 2" in diameter and 40 feet away from the laser source, the required alignment tolerance is  $\pm 0.15$  degrees. This is not achievable in a cost-effective manner in many applications. A second disadvantage with this prior design is that it is a single-pass approach, requiring electronics on both sides of the stack or duct being monitored. Finally, in applications where the use of photopic

light is mandated, the helium-neon laser generates large amounts of heat, is not rugged, is short-lived, and is expensive to replace.

Another disadvantage of all the prior extinction monitor art is that, since maintenance of alignment of the projected beam onto the retro-reflector is necessary to an accurate measurement, rigid and accurate mounting pipes are required. However, in many applications, the desired installation location is on the sides of metal stacks and ductwork which are not mechanically rigid. A significant part of the expense of installing this kind of equipment is associated with adding stiffeners, braces, and the like to existing stacks and ductwork in order to maintain alignment.

In addition to the zero and upscale check, some standards for visible emissions monitoring require a linearity check whereby additional optical filters, corresponding to additional upscale opacity values, are inserted into the measurement path. This is required to be done on a periodic basis, such as on the calendar quarter, and/or following repair or recalibration of the instrument. In most of the prior art systems, this must be done manually.

When very low concentrations of particulate need to be detected, the use of extinction devices is not practical because these devices are measuring transmitted energy. The difference between transmitted energy in a clear stack and transmitted energy with very low dust concentrations becomes vanishingly small and is lost in the signal to noise ratio. Accordingly, for these applications, light scattering instruments are normally used. In these instruments, a beam of light is projected into the stack and a portion of the scattered light is measured. ESC, Durag and Irwin Sick manufacture instruments that essentially measure the energy that is scattered at angles ranging from 90° to 160° with respect to the original propagated direction of the beam. United Sciences manufactures an instrument that measures directly (178° to 180°) backscattered light.

A disadvantage common to all of the prior art involves the issue of calibration checks. The United States Environmental Protection Agency (EPA), as well as the European TUV, requires that a monitor that is being used to demonstrate compliance with particulate emission standards be equipped with a mechanism that can be used to simulate a condition of zero particulate, and a condition equivalent to a predetermined upscale particulate concentration. These must be performed, at a minimum, once every 24 hours. Even when the particulate monitor is not being used for regulatory compliance, the user prefers to have this feature as a part of the system. The prior art in extinction monitors typically achieves the zero condition by interposing into the projected light beam a reflective surface which simulates the effect of the retro-reflector under clear stack conditions. An upscale condition is simulated by interposing an optical filter between the sensing optics and the zero simulation mirror. The prior art in light-scattering moni-

tors typically achieves the zero condition by establishing a direct optical path between the source and the detector via such means as re-orienting the source and detector or inserting a mirror or fiber optic cable, while simultaneously blocking the optical path across the stack. An upscale condition is simulated by interposing an optical filter into that optical path. In the prior art, implementation of this calibration check typically requires the use of additional mechanical moving parts such as solenoids, motors, bearings, and electrical relays.

A related disadvantage of the prior method of performing a zero and upscale calibration check is that, when the measurement pathlength of a transmissometer is changed, the gain factors of the instrument need to be adjusted. This, in turn, requires changing the zero surface such that the optical energy reflected by the zero device is now equivalent to the optical energy corresponding to the cross-stack distance at the new calibration distance. This is most often accomplished by manual adjustment of an iris that alters the cross section of the zero reflective surface. In some instruments, nothing is done to match the optical energy in the zero check mode to the optical energy in the clear-stack path. Instead, the energy mismatch is accounted for in software, which results in less-than-ideal zero and span check because the detector is being evaluated at different operating points than are used for the actual measurement.

The most critical disadvantage of all of the prior art, both extinction and light-scattering, is that the correlation between the optical measurement and the actual particulate concentration in milligrams per cubic meter ( $\text{mg}/\text{m}^3$ ), is highly dependent on the size, shape, and color of the particles being detected. For a fixed concentration of particulate, the optical attenuation, or extinction, or side-scatter, or back-scatter, is maximized when the particle size is about one-half the wavelength of the light that is being used. Particles that are smaller than about one-half of the wavelength of the light being used, as well as particles that are larger than the wavelength of light being used, will be under-reported. Only in the narrow band of particle sizes between about one-half the wavelength and the wavelength will the accuracy of the correlation be relatively unaffected by changes in the particle size.

It follows that, if extinction, back-scatter or side-scatter instruments are being used for correlation to particulate concentration, even an approximate measurement of particle size can provide a way to compensate for this undesirable source of inaccuracy. Without such compensation, it must be recognized that the correlation is chiefly based on the sub-micron particles, whereas most of the actual mass loading in most actual stack emissions is created by particles that are larger than 1 micrometer.

Light scattering calculations based on the Mie Scattering Theory show that the relative intensities of optical scattering of a light beam at various angles within the first lobe of Fraunhofer diffraction is a function the size

of the particles that are causing the scattering. For particles with sizes from one micrometer to 10 micrometers, measurements of relative scattering intensity, at scattering angles of from 1° to 10° from the forward direction, can yield information about the size of the particles. However, none of the prior art includes measurement of light scattering at these angles.

Mie scattering calculations indicate as well that, for a constant mg/m<sup>3</sup> dust loading, the amount of light scattering within the range of forward angles of from 2° to 3° is almost independent of the size of the particles. None of the cited prior art measures light scattering over these angles, chiefly because the maintaining of alignment of a stack-mounted device that would permit measurement at these small angles is difficult. An instrument made by Norsk measures forward scattering, but the angles of the forward scattering that are measured are constrained by the geometry of the stack being measured and cannot be selected to the optimal 2° to 3°, nor can scattering be measured over the range of 1° to 10° for determination of particle size. Furthermore, the Norsk device requires maintenance of alignment to better than 1°, which is difficult to do in an instrument that does not possess automatic beam-steering.

There exists a need for monitoring the efficiency of particulate control devices, including but not limited to electrostatic precipitators and fabric-filter scrubbers. When operating properly, such control devices are very efficient at removing large particles but are much less efficient in removing small particles such as submicron particles. It follows that the ability to monitor both large particles, such as those with diameters of 2.5 to 10 microns, in conjunction with particles that are smaller than one micron, will provide a very useful diagnostic for the maintenance of particulate control devices. Consequently, there exists a need for an extinction monitor which uses a narrow-beam solid-state light source with an automated means to sense the projected angle of the beam and to maintain the alignment of the beam onto a retro-reflector. Such a device could be used with small mounting pipes that could be conveniently be purged via instrument air. The system should be able to perform a zero calibration check and up to three upscale calibration points without the need for additional moving parts. In addition, for those cases in which an extinction monitor is being used for correlation to particulate concentration, a means of determining the approximate particle size distribution is needed to correct the opacity-to-concentration correlation function for changes in particle size distribution. Finally, it would be desirable to have a method for measuring the scattered light at those angles of 2° to 3° at which the scattering intensity is linear with particulate concentration while also being insensitive to changes in particle size.

#### **SUMMARY OF THE INVENTION**

We provide an extinction and forward scattering

monitor containing a steerable, solid state light source which requires low power, is light and rugged, gives off low heat, has long life and can be directly modulated and run on reduced-duty cycling. This light source is collimated into a narrow axial beam and is dynamically steered so as to maintain alignment while overfilling a small retro-reflector. This configuration permits use of mounting pipes of typically 38mm, as compared to 90mm to 150mm pipes required by the prior art. Since the volumetric flow required to purge a pipe goes as the square of the diameter, our monitor requires only 50 to 100 liters per minute of purge air, which can be readily supplied with instrument air. Maintenance of filters and blowers is thereby completely eliminated. Because our invention is self-aligning, it can be installed on stack surfaces and ductwork that are not especially rigid, without the need for support structure modification or frequent realignment by a technician.

One embodiment of our monitor steers the optical beam using rotating cylindrical prisms. Normally, the control of beam position using these devices is complex because the effect of moving one prism is dependent on the current position of the other prism. However, by tilting the optical assembly, it is possible to create an optical configuration in which independent movement of either prism results in movement of the beam in mutually orthogonal directions. This permits use of standard quad detectors and a simple control algorithm.

We further prefer to provide that, in addition to the ability to keep the beam of light centered on a retro-reflector, the mechanism is able to direct the beam in any other desired direction relative to the center of the retro-reflector. By moving the beam to various known angles away from the retro-reflector and then measuring the amount of scattered energy from the beam that nonetheless reaches the retro-reflector, we can create a distribution profile of the light scattered by particulates. The distribution of scattered light is related to the size distribution of the particles, which we then use to calculate the correlation function used to calculate particulate density from the measured opacity. Further, a scattering measurement can be made over the 2° to 3° range over which the correlation between scattering intensity and particulate concentration is independent of particle size.

The ability of the instrument to steer the optical beam also simplifies the zero and upscale calibration checks. Rather than interposing a zero reflector and optical filters into the beam path, our system directs the optical beam onto pre-calibrated surfaces of known reflectivity. Thus, no additional moving parts are required other than those already used to steer the beam. Furthermore, the calibration target is shaped such that, by moving the steered beam slightly, the cross section of the target that is within the beam can be adjusted, thereby eliminating the need for the adjustment iris that is required by the prior art.

Our monitor is useful for measuring particulate concentration, optical extinction or opacity of stacks or ducts

for which prior optical light-scattering instruments, such as are used for determination of particle size in benign environments, have not heretofore been successfully applied. Our device can be used to measure corrosive, hot, vibration-prone environments within large utility and industrial stacks and ductwork.

Other objects and advantages of our monitor will become apparent from a description of the certain present preferred embodiments show in the drawings.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1 is a side view partially in section of a present preferred embodiment of our monitor mounted on a portion of a stack or duct.

Figure 2 is a side view partially in section of the optical assembly of the embodiment of Figure 1.

Figure 3 is a sectional view taken along the line III-III of Figure 2.

Figure 4 is a side view partially in section of the beam steering mechanism of the embodiment of Figure 1.

Figure 5 is an end view of the beam steering mechanism of Figure 4 taken along the line V-V.

Figure 6 is a sectional view showing the quad detector that was taken along the line VI-VI in Figure 2.

Figure 7 is a side view partially in section of the retro-reflector assembly of the embodiment of Figure 1.

Figure 8 is an optical diagram showing the light path which the beam steering mechanism is in a home position.

Figure 9 is an optical diagram similar to Figure 8 showing the light path which the beam steering mechanism is in a full up position.

Figure 10 is an optical diagram similar to Figure 8 showing the light path which the beam steering mechanism is in a full down position.

Figure 11 is a side view partially in section of a second present preferred embodiment of our monitor mounted on a portion of a stack or duct.

Figure 12 is a side view partially in section of the retro-reflector assembly of the embodiment of Figure 11.

Figure 13 is a sectional view taken along the line XIII-XIII in Figure 12.

#### **DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Referring to Figure 1, our system has a retro-reflector assembly 1 and an optical assembly or main assembly 7 which are mounted on opposite sides of a conduit 2. This conduit may be a stack or duct containing the gases resulting from burning fossil fuel, or process gases which contain particulates from industrial processes such as, but not limited to waste incineration, lime kilns, petrochemical processes, food processing, and measurement of dust in mine shafts or vehicular tunnels. The conduit 2 illustrated in the drawings is shown to be quite

small. This was done only for illustrative purposes as we expect our monitor to be used in conduits ranging in size from a less than a meter to over 40 meters in diameter.

A collimated beam of light is projected from a light source 30 in assembly 7, through the conduit 2 in which the opacity or particulate is to be measured, and to a retro-reflector assembly 1 which returns the beam of light to the optical assembly 7. Retro-reflector assembly 1 also serves the function of providing the optical information used by the beam-steering mechanism 10 within assembly 7. We prefer to use a solid-state laser or light-emitting diode (LED) as the light source.

Figure 2 shows the main assembly 7 in more detail.

A light beam indicated in chain line from solid state laser 30 is reflected off beam-splitter 35 to second beam-splitter 34, through beam expander 11 and to beam-steering apparatus 10. From the beam-steering apparatus 10, the beam normally traverses the stack 2. We prefer to provide a 0.75" (1.9 cm.) diameter beam coaxially aligned with retro-reflector assembly 1, overfilling a retro-reflector 20, which is 0.25" (0.64 cm.) diameter shown in Figure 7. Retro-reflector 20 returns the beam through the steering apparatus 10, the beam expander 11 and beam-splitter 34 to beam-splitter 36 which reflects 80% of the beam energy to signal detector 32. Detector 32 preferably is a quad detector able to sense the distribution of the beam on one of four symmetrical detector surfaces. Figure 6 shows such a situation, in which the projected beam indicated by broken circle 40 is focused onto detector 32 as off-axis, being in the negative x, positive y direction. Separate measurement of position signals from the four elements of quad detector 32 provides feedback signals for control of beam-steering apparatus to bring the focused beam to the desired position 41. Addition of the four signals from the four quadrants of the detector 32 gives information about total attenuation of the beam across the stack, which is a measure of opacity.

Beam-splitter 36 preferably is selected to allow 20% of the beam energy to be focused onto an eyepiece 31, allowing observation of the alignment. The portion of the beam that is transmitted through beam-splitter 35 is focused into reference detector 33 and is used to establish the ratio of the transmitted beam intensity as determined by the total signal from quad detector 32 to the laser intensity as determined by reference detector 33.

As illustrated in Figures 4 and 5, the preferred beam-steering apparatus 10 consists of two similar assemblies, each containing one of two wedge prisms 22a and 22b. Each prism is axially aligned with beam expander 11. As can be seen in Figure 5, there is a servo motor 24, timing belt 29 and encoder 25 associated with each prism. Each prism can be independently rotated via bearings 23, timing belt 29 driven by servo motor 24 and encoder 25. Each prism is associated with a homing switch 26 which is used as a reference point for the encoder 25. Homing switch 26 is activated once per revolution of the associated prism 22a or 22b. Each encoder

is related to a prism via a 4:1 gear ratio such that the encoder rotates 4 times per prism rotation. Each encoder 25 has three square-wave outputs: (1) a once-per-encoder pulse, (2) a 0°-phase pulse for each 0.18 degrees of rotation of the encoder, and (3) a 90°-phase pulse, that lags the 0°-phase pulse by a quarter-cycle, for each 0.18 degrees of rotation of the encoder. The 0° and 90° phase pulses indicate which direction the encoder is turning. The encoder resolution, combined with the 4:1 gear ratio, enables the system to know the rotation of the prisms by  $\pm 0.045^\circ$ .

We prefer to use wedge prisms which are able to cause a deflection of  $6^\circ$  in the direction of the beam passing through it. Rotating either prism about  $360^\circ$  causes the expanded laser beam to describe a circle corresponding to a  $6^\circ$  deflection of the beam. By independently controlling the motion of the two prisms, the beam can be steered to any direction inside a  $12^\circ$  deviation from its original direction. Since the system can identify prism rotation to within  $\pm 0.045^\circ$ , and since a  $180^\circ$  prism rotation creates a change of direction of  $6^\circ$  in the projected beam, it follows that we are able to identify the beam direction to within  $\pm(0.045/180)(6^\circ) = \pm 0.0015^\circ$ . At a distance of 130 feet, or about 40 meters, this corresponds to a beam deflection of

$(130 \text{ feet})\tan(\pm 0.0015^\circ) = \pm 0.034 \text{ inches or } \pm 0.86 \text{ cm}$ . This is more than adequate resolution for maintaining the beam onto the retro-reflector.

Figure 8 shows the situation in which the prisms are anti-aligned so as to produce no change in the direction of the beam. This is referred to as the Home Position of the beam. Figure 9 shows the situation in which the two prisms are aligned with the thick edges of the prisms vertically aligned upward. We call this the Full Up direction of the beam which strikes surface 39 on the retro-reflector assembly or slack wall. When wedge prisms are used that create a deflection of  $6^\circ$  angle  $\Theta$  will be  $12^\circ$  above the optical axis. Figure 10 shows the situation in which the two prisms are aligned with the thick edges of the prisms vertically aligned downward. We call this the Full Down direction of the beam. When wedge prisms are used that create a deflection of  $6^\circ$  angle  $\Theta$  will be  $12^\circ$  down from the optical axis.

If, from the Full Up position of Figure 9, the two prisms are rotated in opposite directions, one clockwise and one counter-clockwise, by  $45^\circ$ , it is straightforward trigonometry to show that the beam will be steered to a direction  $8.5^\circ$  vertically above the Home Position. It is also apparent that, because the thick side of each prism is now at a  $45^\circ$  angle with respect to the vertical and horizontal planes, that a small rotations of either prism, with the other held stationary, will produce a movement in the projected beam that is at approximately a  $45^\circ$  angle with respect to the vertical and horizontal planes. The effect of individual moving Prism 22a will, in addition, be orthogonal to the effect of moving prism 22b. Referring again to Figure 6, the quad detector 32 can be oriented within the optical system such that the de-

tor's x-axis is predominately associated with movements of prism 22a while the detector's y-axis is predominately associated with movements of prism 22b. This makes possible the development of simpler control algorithms in the region of  $8.5^\circ$  beam direction than is possible in the near-region of other beam directions.

Although we prefer to use two prisms to steer the beam, several other mechanisms could be used. We could provide a pair of mirrors and steer the beam through orthogonal movement of the pair of mirrors. A concave lens or combination of lenses could be used. In that embodiment linear movement of an orthogonally oriented concave lens will steer the beam.

As shown in Figures 1 and 2, we prefer that the entire apparatus of laser, beam expander, steering apparatus, detectors and beam-splitters be tilted downward at an angle  $\Delta$  of  $8.5^\circ$  with respect to the axis formed by the center of the front window 38 and retro-reflector 20 in the retro-reflector assembly 1. This results in a configuration such that when the beam is pointing out of the cone angle defined by the mounting nozzle 3, prisms 22a and 22b will be oriented such that the mutually orthogonal effect of individual rotations will apply.

As seen most clearly in Figure 2, the laser, beam-splitters, beam expander and detectors are affixed to an optical bench 12 that preferably is a precision casting. The components, along with the beam-steering apparatus 10, are affixed to a base-plate 9 mounted on a plate 8 which also contains the front window 38. Intermediate housing 51 provides access to a calibration target to be described later. Purge housing 52 includes provision for a purge port 53 connected to nozzle 3 which provide protection of the window 38 and calibration target 13 from heat and gases. Purge air is supplied through line 54 that preferably is connected to a source of dry, filtered, instrument air. The overall apparatus is designed so that the optical assembly 7 and the retro-reflector assembly 1 each fit onto a system flange 4 which contacts a seal 5. The beam steering assembly is preferably controlled by a microprocessor (not shown) positioned within the optical assembly. Power and communication lines (not shown) for the microprocessor, motors, encoders light source and detectors are provided through conduits 55. Purge air for the retro-reflector is provided through conduit 56. The entire assembly is protected from rain, dust and other factors by a cover 14, having a window 37 opposite eyepiece 31.

Figure 3 is an inboard view of the intermediate housing 51. The calibration target as depicted shows in chain line alternate positions of the beam 107 as a  $1.5''$  projected spot which may be steered to one of five locations on the target. One of the five locations is a flat black or other absorbing surface 104 which serves to simulate the situation of 100% opacity in the conduit, or infinitely high particulate loading in the conduit which does not permit any of the beam to cross the conduit. Each of the other four calibration targets includes a reflective disc 106 and reflective rectangle 105 which,

when co-illuminated by the beam, reflect back an amount of energy approximately equal to the energy that would be reflected from retro-reflector 20 under clear-conduit conditions. By adjusting the steering of the beam to include more or less of reflective rectangle 105, the equivalency of the calibration target and cross-conduit retro-reflector 20 can be achieved with any desired degree of accuracy. This feature of our invention eliminates the need for mechanical adjustment of a calibration iris. A linearity check, to any desired upscale opacity, can be achieved by affixing neutral density filters of known optical transmission, to calibration targets.

As shown in Figure 3, the centers of the four reflective discs 106, as well as the centerlines of the four reflective rectangles 105 are arranged symmetrically about the Home Position of the beam. This means that, once the prism positioning needed to establish equivalency with retro-reflector 20 is established the other four calibration locations can be located by the simple procedure of rotating both prisms by a number of degrees equivalent to the angular separation of the targets from the home position.

Additional details of the retro-reflector assembly 1 are shown as Figure 7. Flange 4, seal 5, and purge nozzle 3 are equivalent to those in Figure 2. A purge air sensing switch 27 is shown monitoring the pressure drop across the purge venturi.

Evaluation of the opacity caused by particulate in the stack provides only partial information about particulate concentrations. Additional information is achieved by measuring and evaluating the angular distribution of light scattered from the beam. This can be done by the second preferred embodiment of our monitor shown in Figures 11, 12 and 13. Figure 11 depicts the situation in which the system first aligned the beam across the stack by using signals from the quad detector 32 to enable the beam-steering apparatus 10 to center the beam on and about retro-reflector 20. Both opacity and near-forward scattered light can be measured in this configuration. The beam steering apparatus 10 now uses information from the encoder 25 to point the beam at one of a number of desired angles such that no energy from the primary 1.5" beam is entering nozzle 3. The only optical energy entering nozzle 3 will be due to scattered light from particulates in the conduit 2 as indicated by particle P in Figure 11. Note that the size of purge nozzle 3 on the source side of the conduit is made larger to enable larger steered angles to be achieved. Preferably angles of from 0° to 6° will be used.

The details of how the scattered light is measured can be understood from Figures 12 and 13. Retro-reflector 20 is carried in a housing 42 that is bonded to the center of a glass plate 43. When the diameter of the light beam from the solid state light source is larger than the retro-reflector or that beam is directed to a position adjacent housing 42 light will enter into a Cassegrain Telescope 110. Although we show the use of a Cassegrain Telescope for the gathering of scattered light, any one

of a number of well-understood designs involving lenses and/or mirrors may also be used. That light will strike primary mirror 46 and be reflected to secondary mirror 47 located behind the retro-reflector 20. This folded angular beam of scattered energy is thereby focused onto one end of fiber optical cable 111. The other end of cable 111 is connected to a detector within the optical housing 7 (not shown) where the information is processed, preferably by the same microprocessor circuitry as is used for the opacity measurement. The optimal use of the invention for measuring the concentration and size distribution of particulates is as follows. When servo controls are used to maintain the collimated light beam of the retroreflector, the total optical attenuation is created primarily by submicron particulates, with a much smaller contribution from larger particulates. If the beam is steered such that the intensity of scattered light entering the Cassegrain telescope is measured for scattering angles of 1 degree to 10 degrees, the ratios of scattering intensities at various of these angles provide information about the distribution of particle sizes to from 1 micron to 10 microns. This information, in addition to satisfying the needs of anticipated particulate monitoring requirements, can be used to subtract the effect of large particles from the total attenuation data, such that the total attenuation data provides information about particulate concentration of only the submicron particles. Finally, our calculations from Mie scattering theory indicate that, when the beam is steered such that the light entering the Cassegrain telescope has been scattered by 2 to 3 degrees, the intensity of the detected light will be proportional to the total mass of all particulates, irrespective of particle size.

Measurement of the scattering intensity at more than one angle can provide an estimate of the particle size distribution. Larger particles scatter light more intensely in the near-forward direction, whereas smaller particles scatter light more uniformly in all directions. The ratio of scattering at two angles (e.g., (scattering at 10°)/(scattering at 5°) is a function of particle size. For instance, using light of 600 nanometer wavelength, the 10°:5° scattering intensity ratio is approximately 0.1 for particles with diameter of 3.4 micrometer, but is approximately 0.8 for particles with diameter of 3.1 micrometer. Measurement of scattering angles as small as 1°, and scattering ratios such as 2°:1° or 5°:2°, permit calculation of particle sizes over the range of 1 micrometer to 10 micrometer. Effective application of these optical scattering phenomena to the sizing of particles in large stacks and ducts, however, has not heretofore been practical prior to the development of beam-steering methods.

We prefer to provide electronic and microprocessor components and software programs in the electronic module 15, shown in Figure 2, to provide automatic alignment, to enable the system to re-establish alignment following power failures, and to provide means for automatic checks of system calibration without the need

of moving parts other than the beam-steering mechanism. Electronic module 15 includes a drive controller 16 which can be used to operate the laser 30 in a pulsed mode so as to reduce the fraction of time that the laser 30 is operating so as to extend laser life.

Although we have shown and described certain present preferred embodiments of our monitor and method for monitoring size, distribution and concentration of particulates in a conduit, it should be distinctly understood that our invention is not limited thereto but may be variously embodied within the scope of the following claims.

#### Claims

1. A method for monitoring size distribution and concentration of particulates in a conduit (2) which has a window that allows passage of at least one light beam through the window and across the conduit characterized by:
  - a. positioning a solid state light source (30) so that at least one light beam from the solid state light source (30) may be passed through the window and across the conduit (2) along an optical axis and along at least one scattering axis which intersects the optical axis at a selected angle  $\Theta$ ;
  - b. positioning at least one detector (32) on the optical axis to receive the light beam from the solid state light source (32) after that light beam has passed through the conduit (2) along the optical axis and to receive light scattered from light beams striking particulates in the conduit (2) which detector (32) produces a signal corresponding to intensity of light received by the detector (32) the signal being useful for measuring at least one of opacity of a medium passing through the conduit (2) and light scattered by particulates in the conduit (2);
  - c. passing at least one light beam along at least one scattering axis;
  - d. detecting light scattered from the at least one light beam striking particulates within the conduit (2) when the at least one light beam is aimed at a known angle  $\Theta$ ;
  - e. measuring an intensity of the detected light;
  - f. determining what fraction of the at least one light beam has been detected; and
  - g. using the intensity of scattered light at at least two angles to calculate size distribution of particles in the conduit (2).
2. The method of claim 1 wherein the intensity is measured at a scattering angle  $\Theta$  of between 2 and 3 degrees so as to form a signal that is proportional to a concentration of particles within the conduit (2)
3. The method of claim 1 wherein the detector (32) is within a housing (14) that also contains the solid state light source (30) and also characterized by reflecting the at least one light beam back through the conduit (2) to the detector (32) after the light beam from the solid state light source (30) has passed through the conduit (2).
4. The method of claim 1 also characterized by:
  - a. splitting the at least one beam which has passed through the conduit into a first beam and a second beam;
  - b. directing to the first beam to the at least one detector (32); and
  - c. directing the second beam to a second detector (33).
5. The method of claim 1 also characterized by passing light scattered by particulates from the at least one beam through collection optics (110) before light scattered by particulates from the at least one beam reaches the at least one detector (32).
6. The method of claim 8 also characterized by passing light scattered by particulates from the at least one beam of light through a fiber optic cable (111) to an analyzer after light scattered by particulates from the at least one beam of light has passed through the collection optics (110).
7. The method of claim 1 also characterized by passing the at least one beam of light through a pair of rotatable wedge prisms (22) in the optical path such that the at least one light beam is directed to a retro-reflector (20) when the prisms (22) are orthogonal to one another, as a result of which independent motion of either prism (22) will cause orthogonal movement of the light beam from the solid state light source (30).
8. The method of claim 9 also characterized by tracking positions of the first wedge prism (22) with a first encoder (25) connected to the first wedge prism (22) and tracking positions of the second wedge prism (22) with a second encoder (25) connected to the second wedge prism (22).
9. The method of claim 1 also characterized by:
  - a. providing a calibration assembly (13) having at least one region of a known reflectivity which assembly (13) is positioned so that light from the solid state light source may be directed onto the at least one region for reflection to the detector (32);



- b. directing at least one light beam onto the at least one region so that the at least one light beam is reflected to the detector (32);  
 c. measuring an intensity of light reflected from the at least one region; and  
 d. comparing that measurement with an expected intensity corresponding to the at least one region.
10. The method of claim 1 also characterized by:  
 a. determining an opacity of the medium passing through the conduit (2); and  
 b. using the intensity of scattered light at least two angles along with the opacity to calculate a size distribution of particles in the conduit.
11. A method for monitoring size distribution and concentration of particulates in a conduit (2) which has a window that allows passage of at least one light beam through the window and across the conduit (2) characterized by:  
 a. positioning a solid state light source (30) so that at least one light beam from the solid state light source (30) may be passed through the window and across the conduit (2) along an optical axis and along at least one scattering axis which intersects the optical axis at a selected angle  $\Theta$ ;  
 b. positioning at least one detector (32) on the optical axis to receive the light beam from the solid state light source (30) after that light beam has passed through the conduit along the optical axis and to receive light scattered from light beams striking particulates in the conduit (2) which detector (32) produces a signal corresponding to intensity of light received by the detector (32) the signal being useful for measuring at least one of opacity of a medium passing through the conduit (2) and light scattered by particulates in the conduit (2).  
 c. passing at least one light beam along at least one scattering axis;  
 d. detecting light scattered from the at least one light beam striking particulates within the conduit (2) when the at least one light beam is aimed at a known angle  $\Theta$ ;  
 e. measuring an intensity of the detected light;  
 f. determining what fraction of the at least one light beam has been detected;  
 g. determining an opacity of the medium passing through the conduit (2); and  
 h. using the intensity of scattered light at at least two angles along with the opacity to calculate a size distribution of particles in the conduit (2).
12. A monitor comprised of:  
 a. a housing (14) sized and configured for attachment to a conduit (2) and having a window (38) through which light may pass;  
 b. a solid state light source (30) within the housing (14);  
 c. a beam steering unit (10) within the housing (14) and having a pair of colinear rotatable wedge prisms (22) positioned to direct a light beam from the light source (30) through the window and across the conduit (2); and  
 d. at least one detector (32) positioned to receive the light beam from the solid state light source (30) after that light beam has passed through the conduit (2) and to receive light which has been forward scattered after striking particles in the conduit (2) which detector (32) produces a signal corresponding to intensity of light received by the detector (32) the signal being useful for measuring at least one of opacity of a medium passing through the conduit (2) and light scattered by particulates in the conduit (2).
13. The monitor of claim 12 also characterized by a calibration assembly (13) having at least one region of a known reflectivity which assembly (13) is positioned within the housing (14) so that the beam steering unit (10) may direct a light beam onto the at least one region for reflection to the detector (32).
14. A monitor comprised of:  
 a. a housing (14) sized and configured for attachment to a conduit (2) and having a window (38) through which light may pass;  
 b. a solid state light source (30) within the housing (14);  
 c. a beam steering unit (10) within the housing (14) and positioned for directing a light beam from the light source (30) through the window (38) and across the conduit (2); and  
 d. at least one detector (32) positioned for receiving the light beam from the solid state light source (30) after that light beam has passed through the conduit (2) and for receiving light which has been forward scattered after striking particles in the conduit (2) which detector (32) produces a signal corresponding to intensity of light received by the detector (32) the signal being useful for measuring at least one of opacity of a medium passing through the conduit (2) and light scattered by particulates in the conduit (2).
15. The monitor of any previous claim wherein the detector (32) is within the housing (14) and also characterized by a retro-reflector (20) for reflecting back through the conduit (2) to the detector (32) a light

beam from the solid state light source (30) which has passed through the conduit (2).

16. The monitor of claim 15 also characterized by detection optics (110) positioned near the retro-reflector (20) which detection optics can detect scattered light from the light beam when the light beam is aimed at a known angle relative to the detection optics. 5
17. The monitor of claim 16 wherein the detection optics (110) is characterized by a Cassegrain telescope (110). 10
18. The monitor of claim 17 also characterized by a fiber optic cable (111) connected between the Cassegrain telescope (110) and the housing (44). 15

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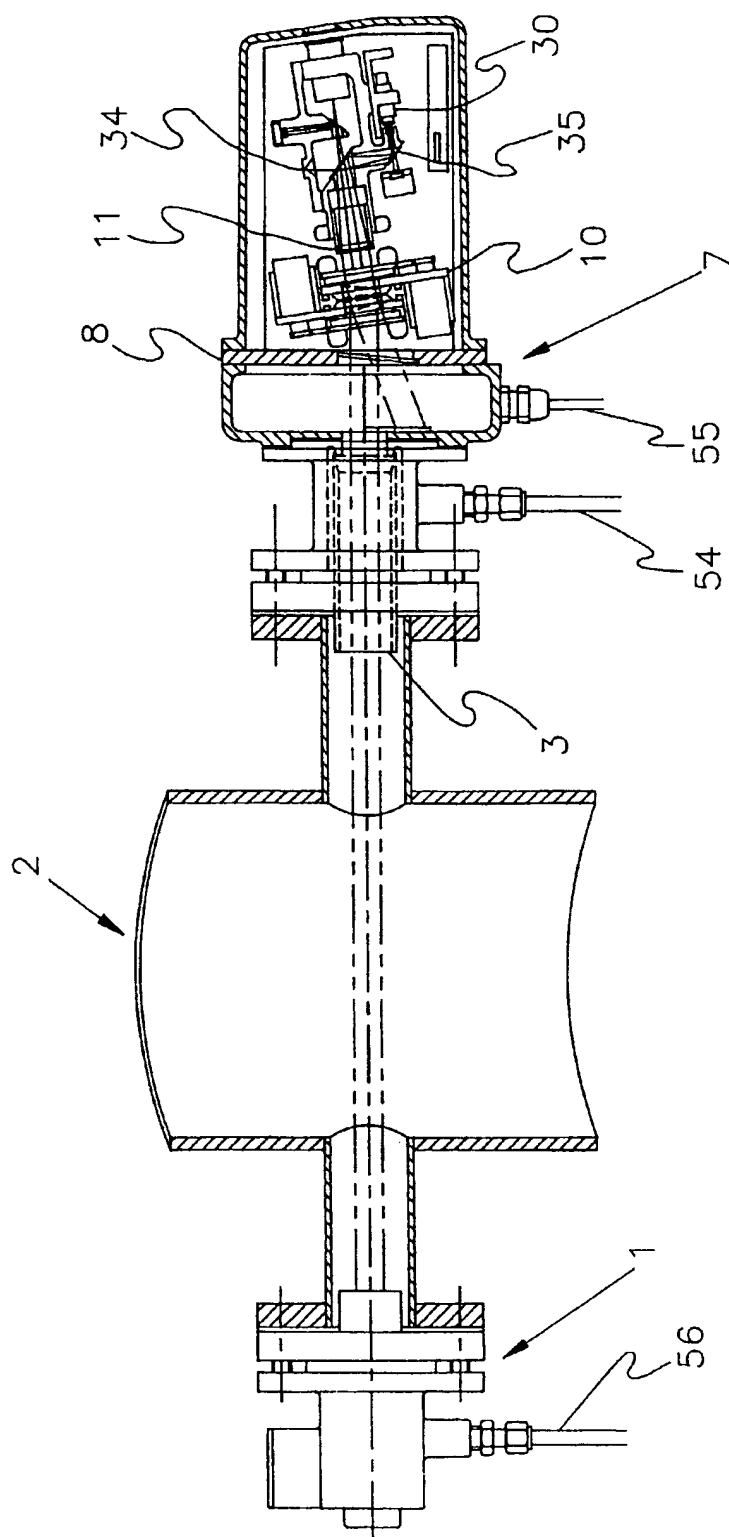
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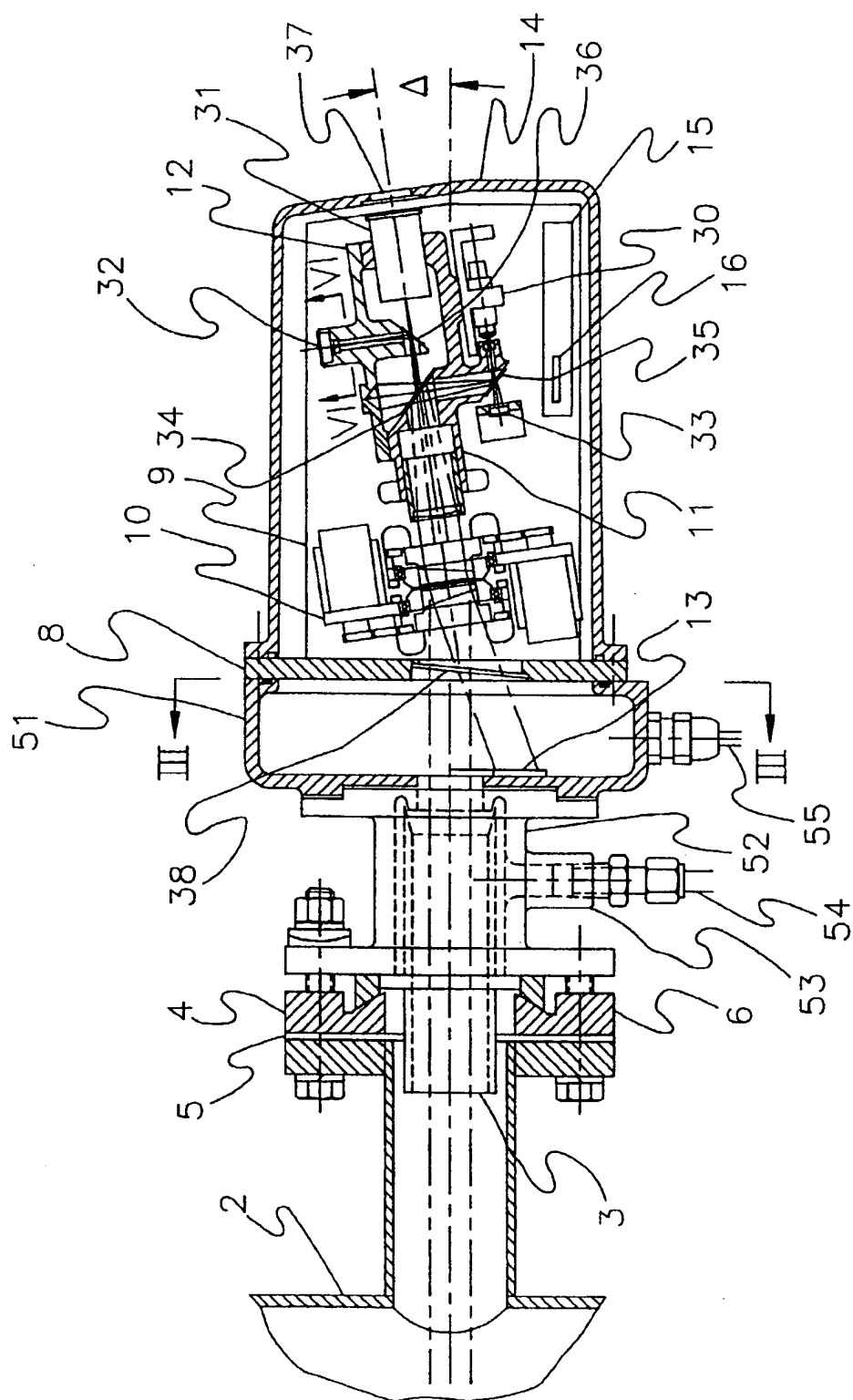


FIGURE 2

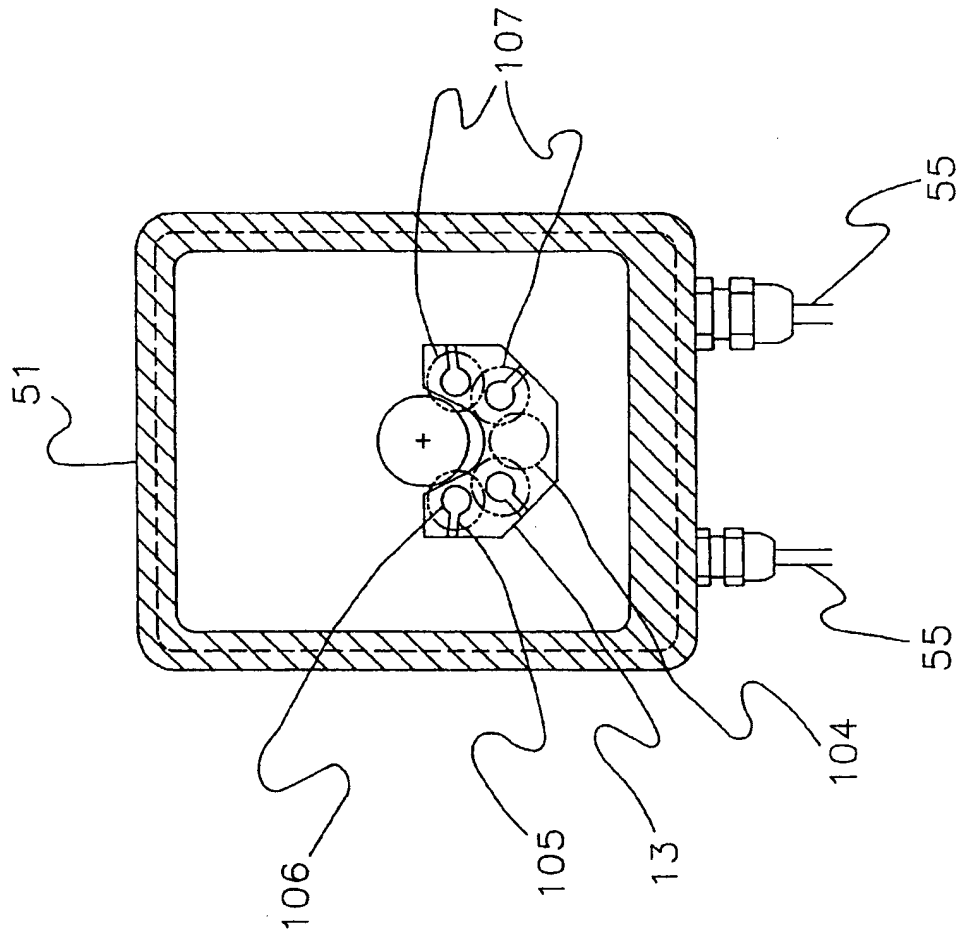
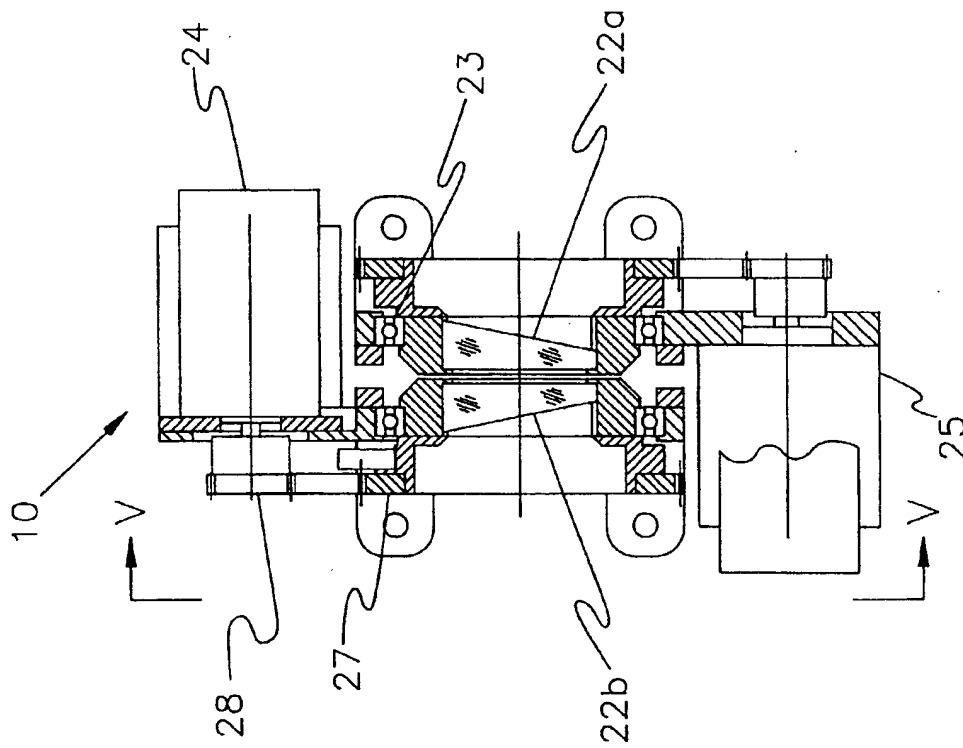
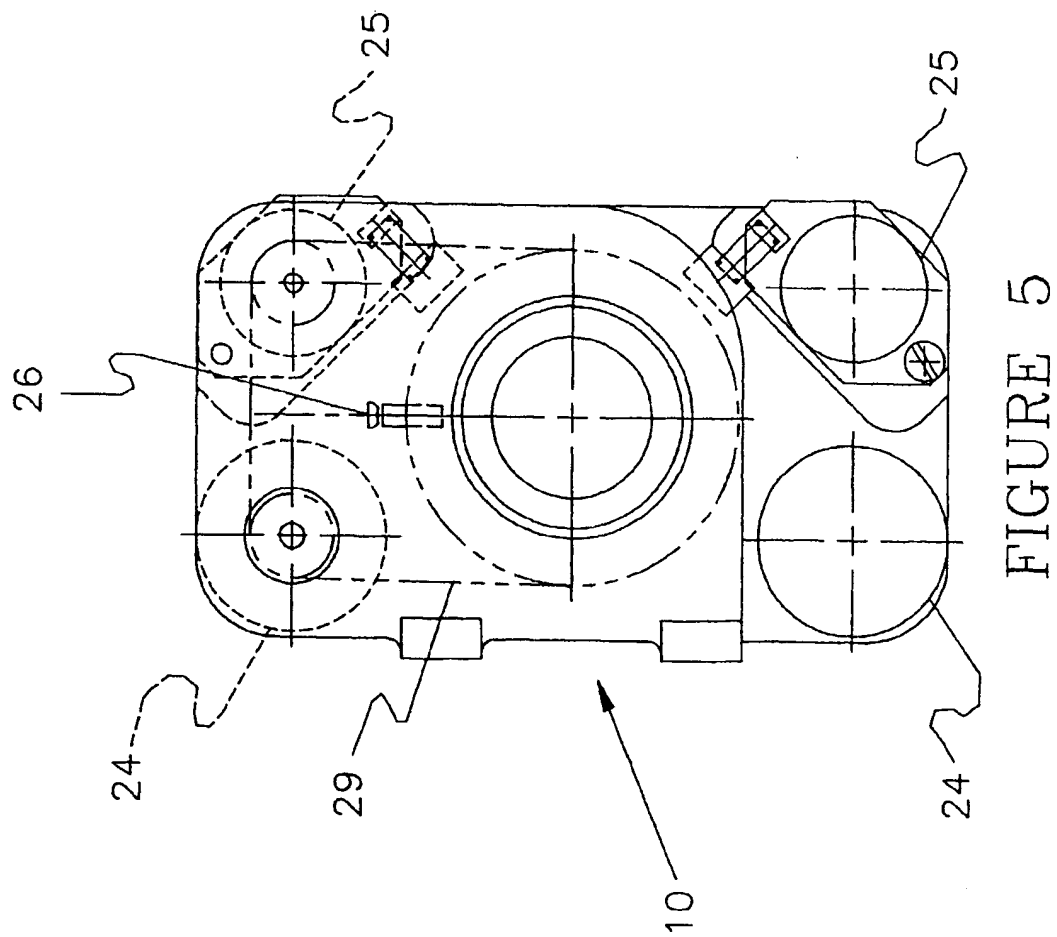


FIGURE 3





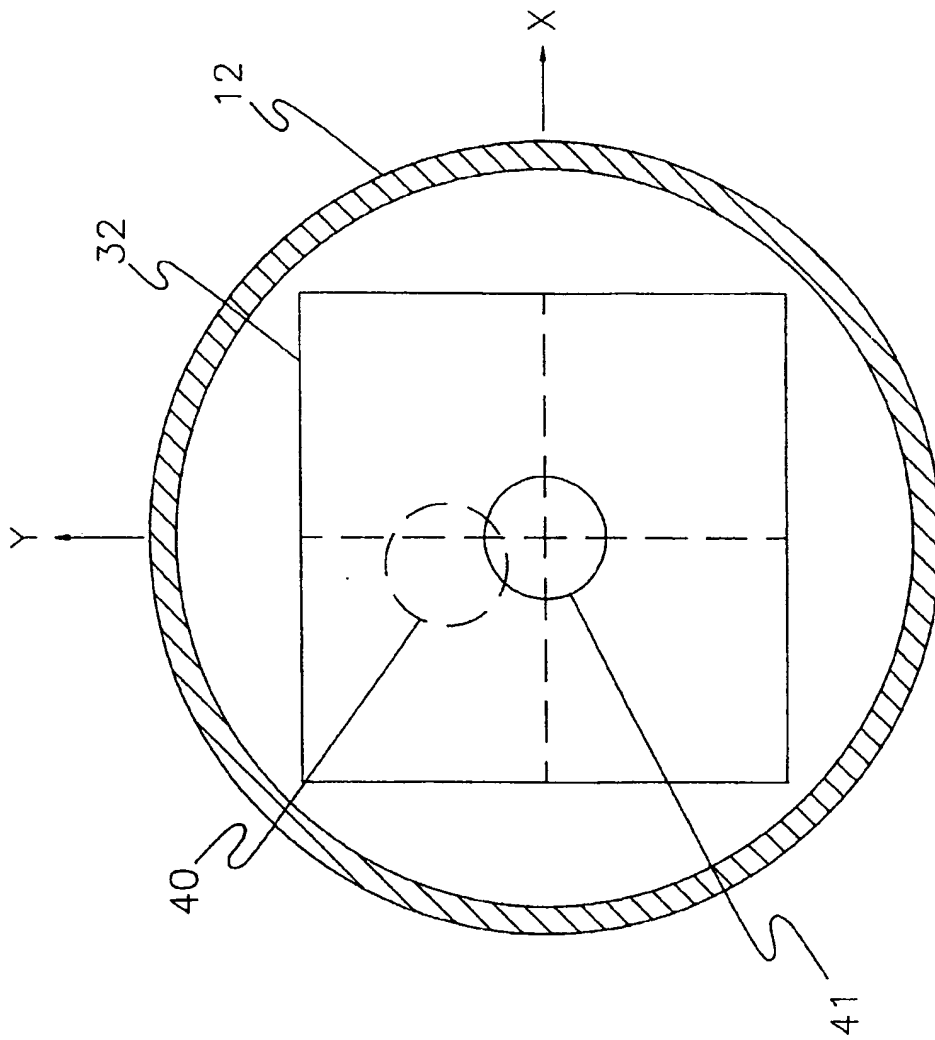
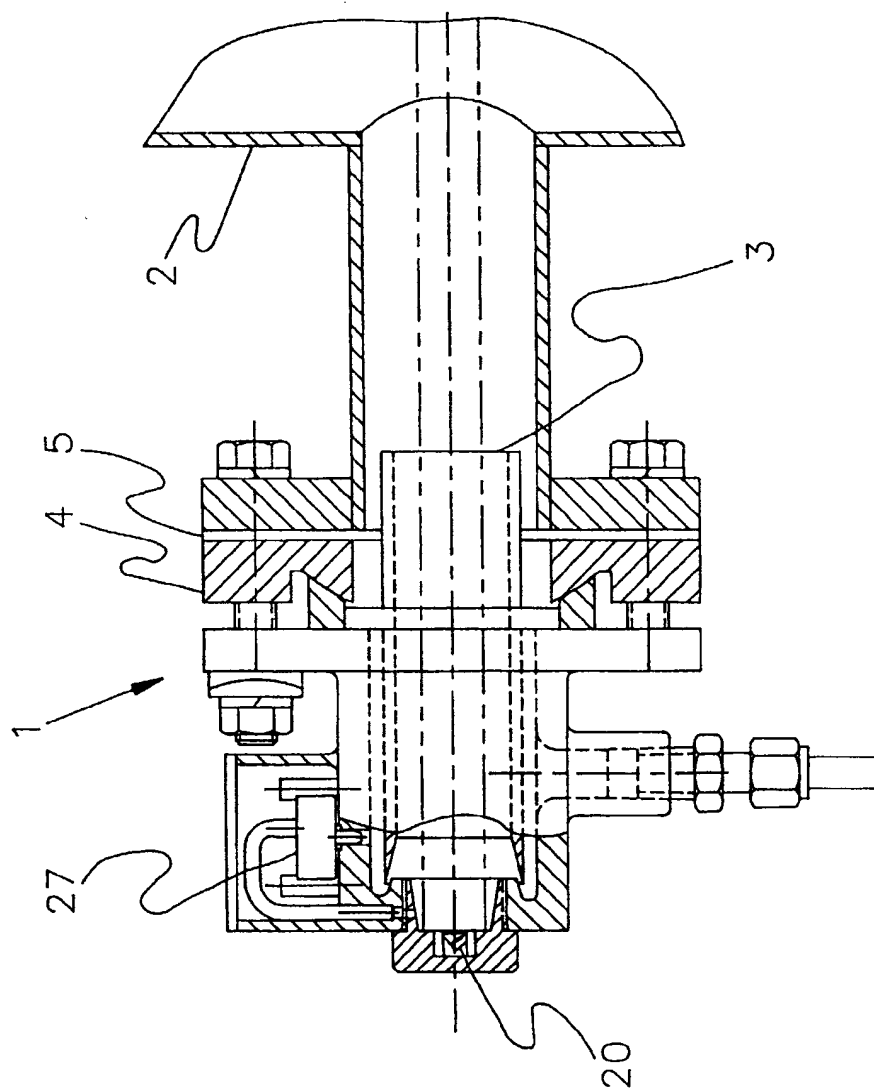


FIGURE 6





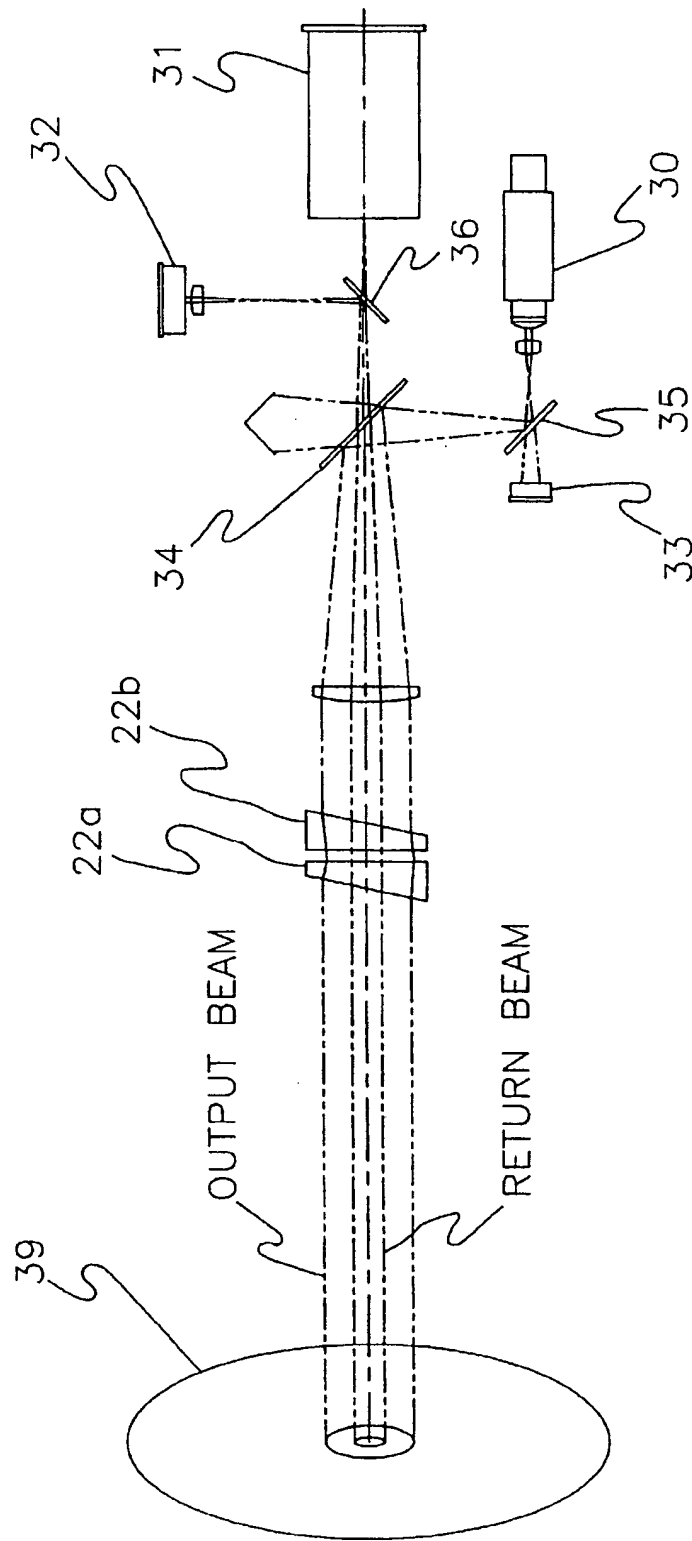


FIGURE 8

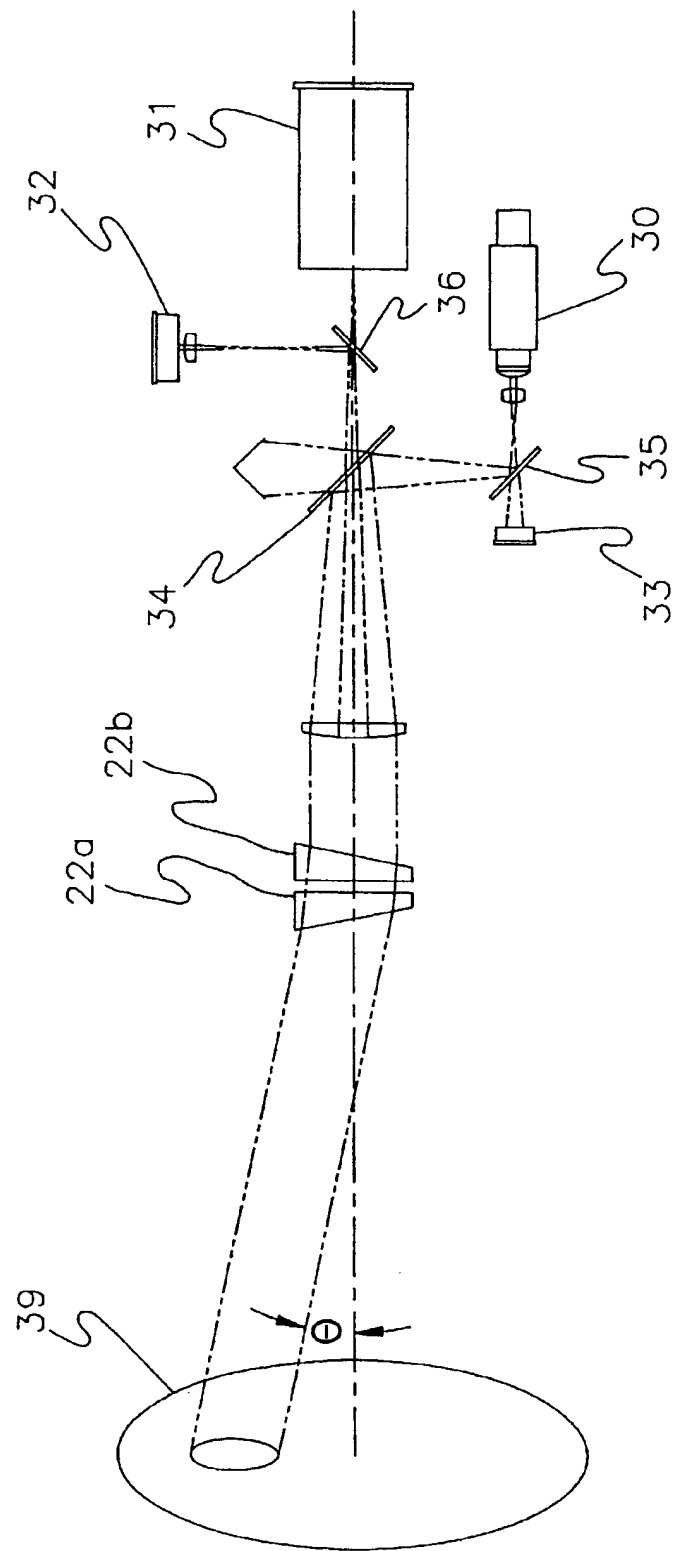


FIGURE 9

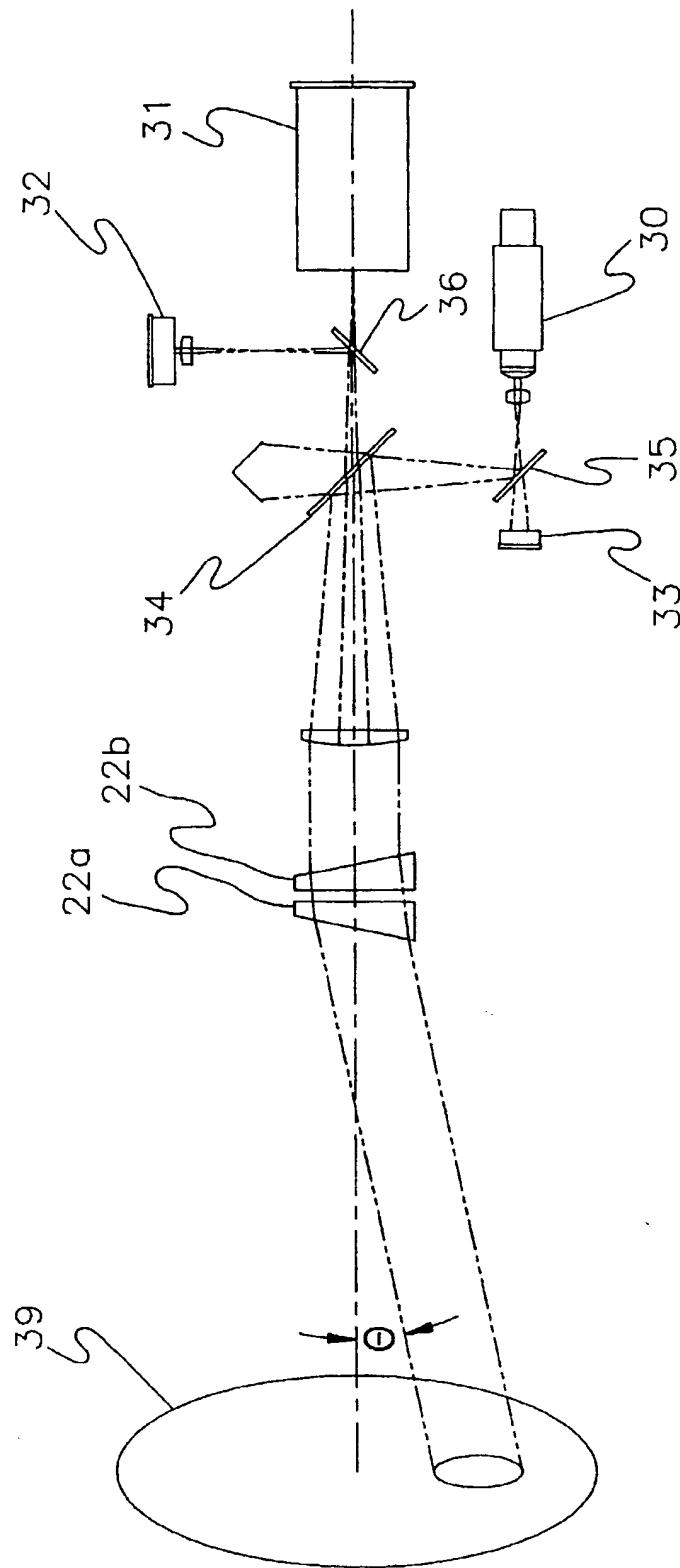


FIGURE 10

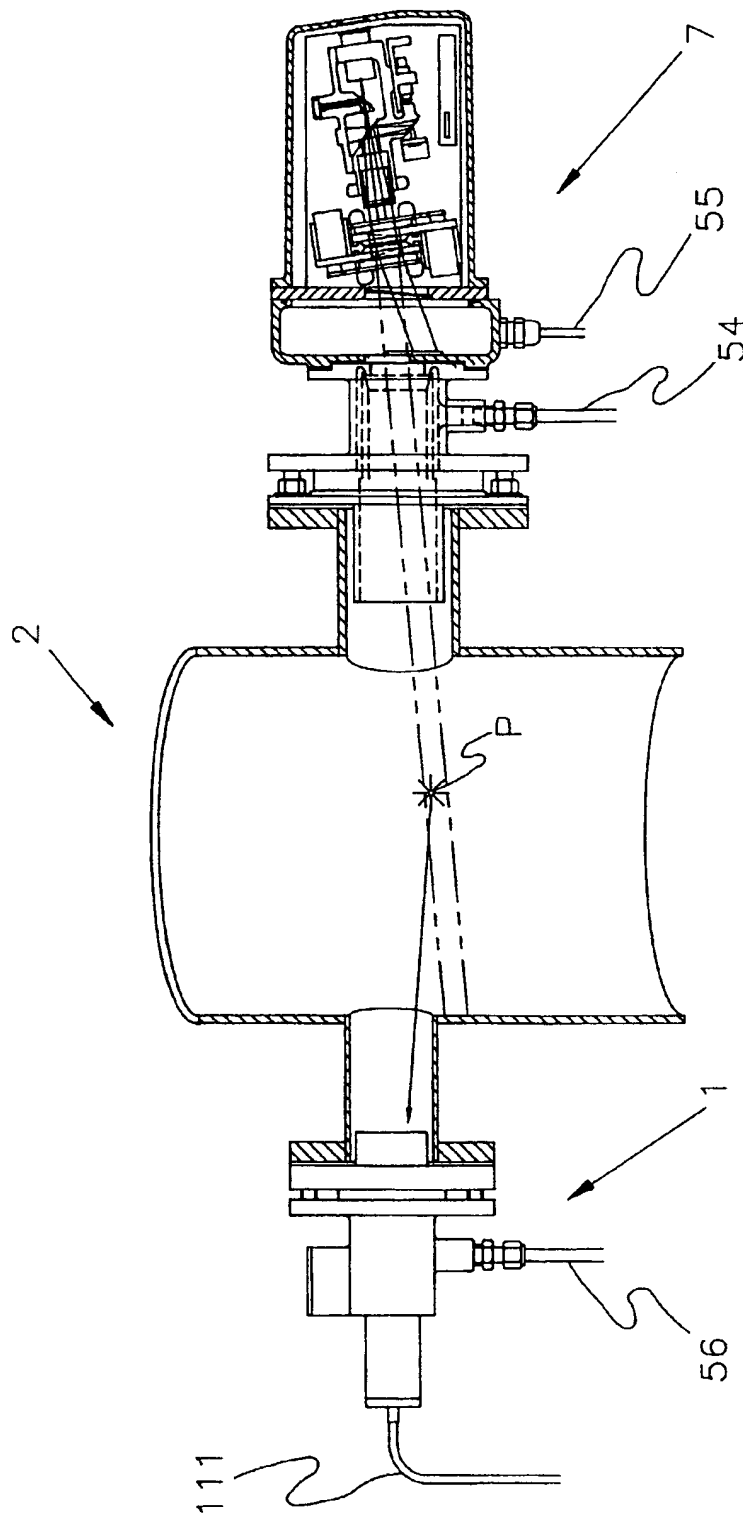
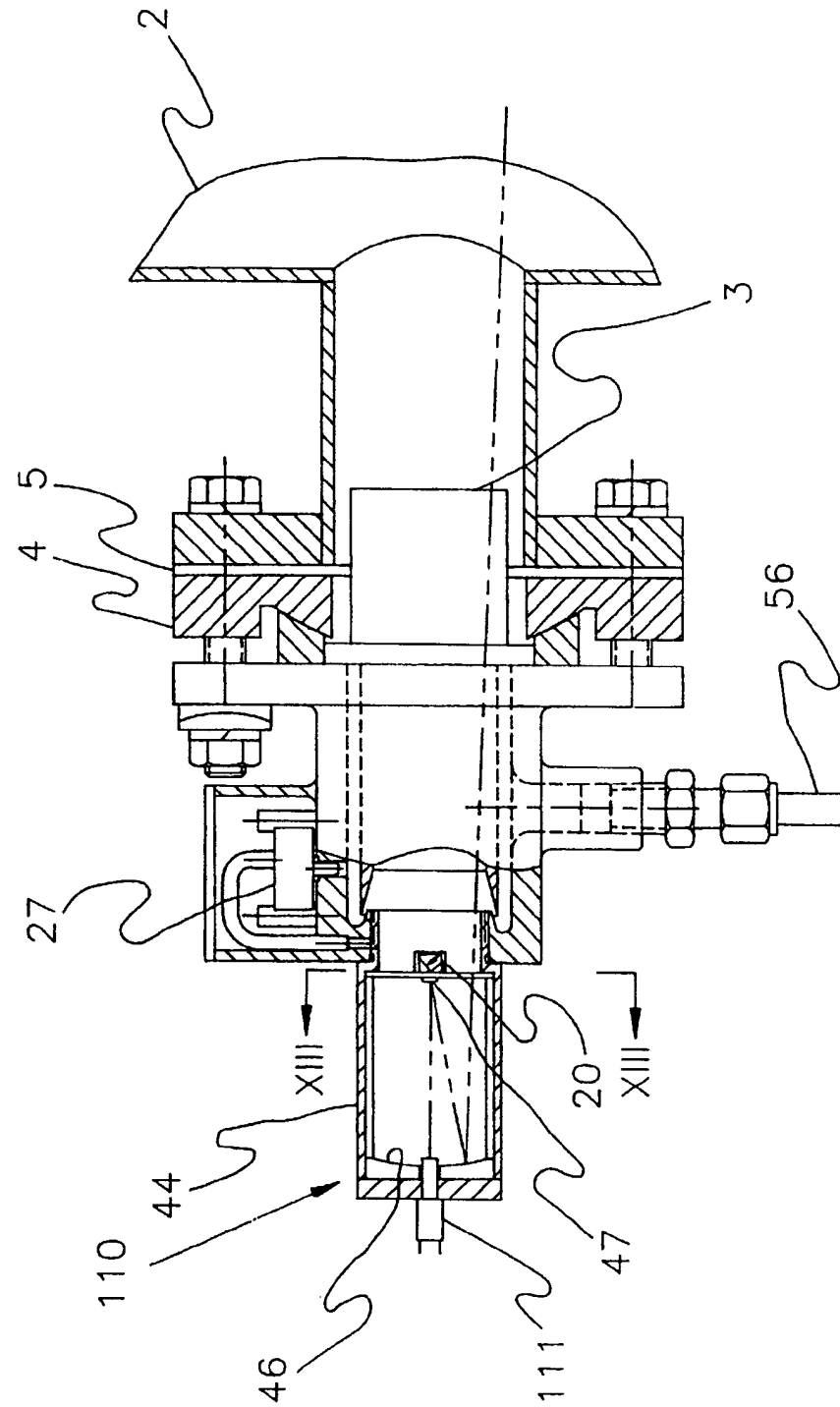


FIGURE 11



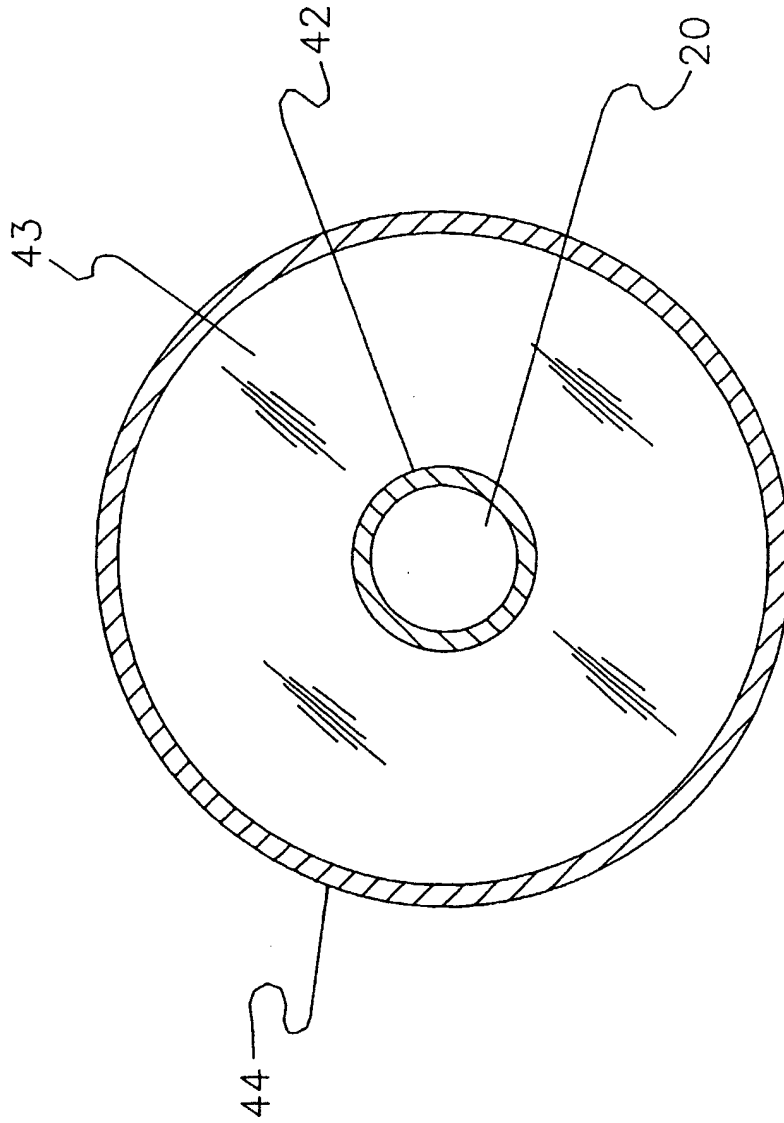


FIGURE 13